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(54) **SYSTEMS AND METHODS FOR DATA EXCHANGE BETWEEN BINAURAL HEARING DEVICES**

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(52) **U.S. Cl.**
CPC ***H04R 25/407*** (2013.01)

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CPC H04R 25/00; H04R 25/55; H04R 25/558
USPC 381/312–331, 380–381
See application file for complete search history.

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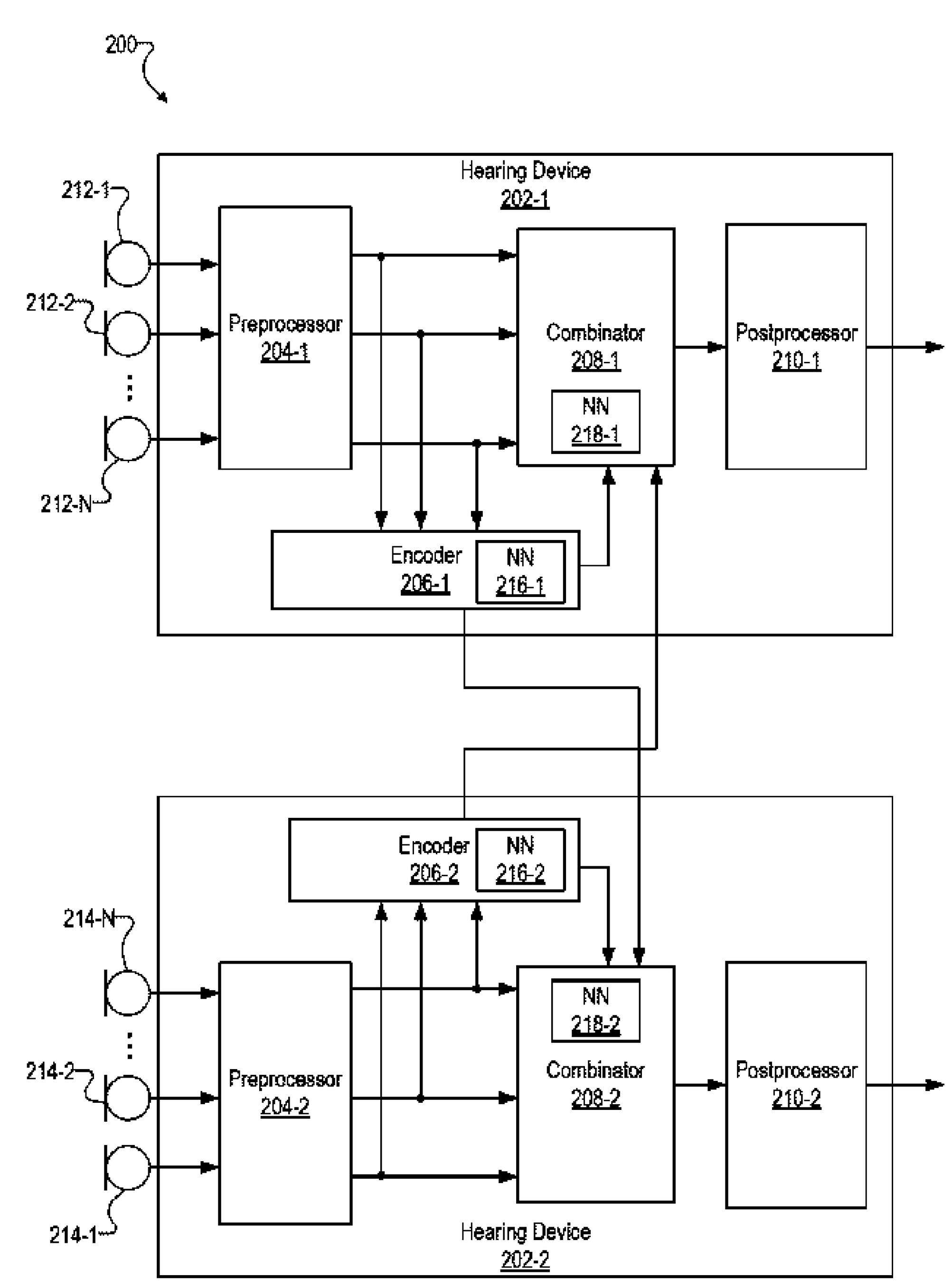
(57) **ABSTRACT**

An exemplary system comprises a first and second hearing device associated with a first and second ear of a user, respectively. The first hearing device is configured to detect a first audio signal representative of audio content, generate a first intermediate signal representation (ISR) corresponding to the first audio signal, the first ISR comprising a sparsely-encoded non-audio signal having a complexity measure that is below a threshold, and transmit the first ISR to the second hearing device. The second hearing device is configured to detect a second audio signal representative of the audio content, generate a second ISR corresponding to the second audio signal, and transmit the second ISR to the first hearing device. The first hearing device is further configured to generate, based on the first and second ISRs, an output audio signal, and provide the output audio signal to the first ear of the user.

17 Claims, 6 Drawing Sheets



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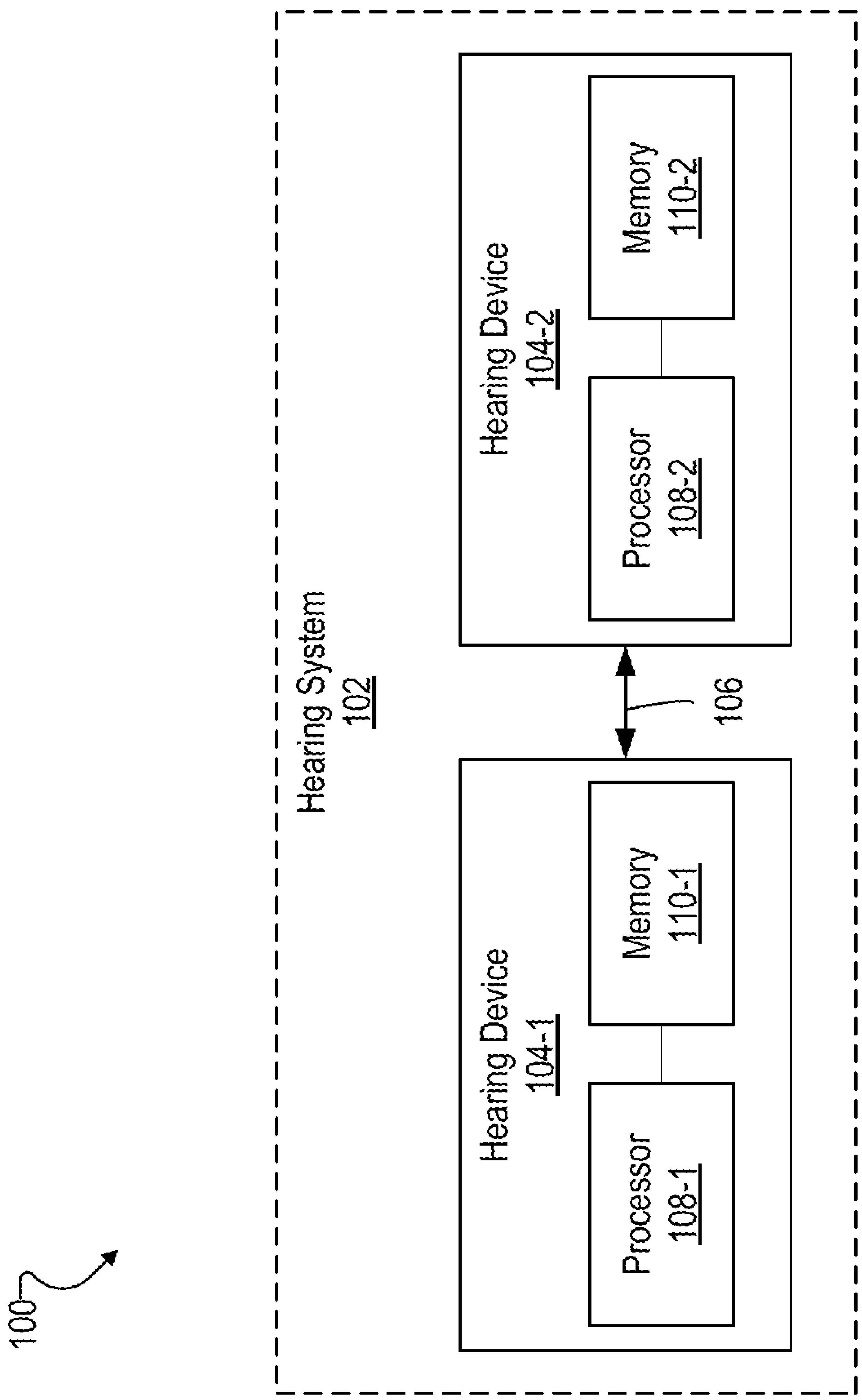

100
Hearing System
102
Hearing Device
104-1
Processor
108-1
Memory
110-1
106
Hearing Device
104-2
Processor
108-2
Memory
110-2

Fig. 1

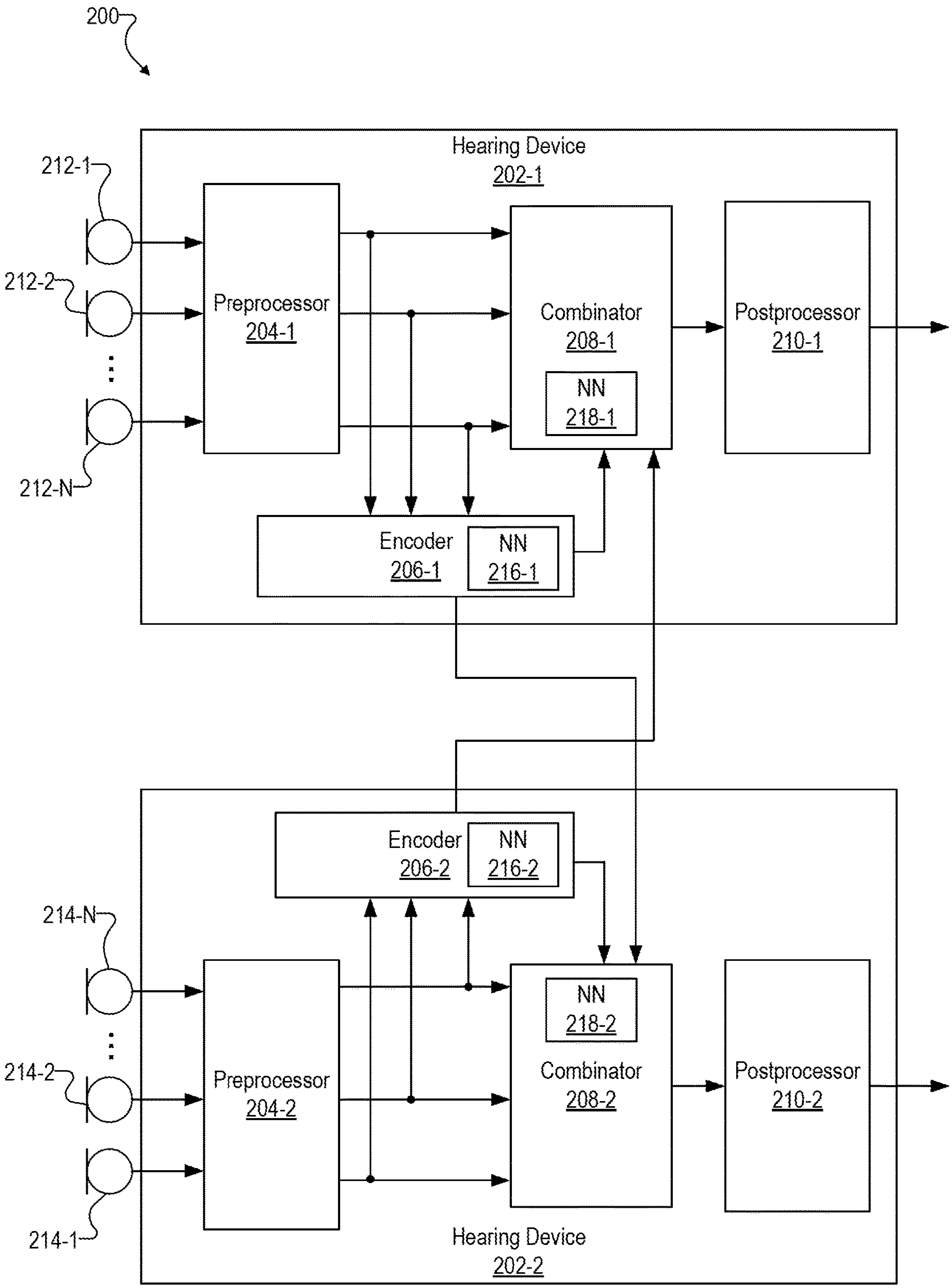
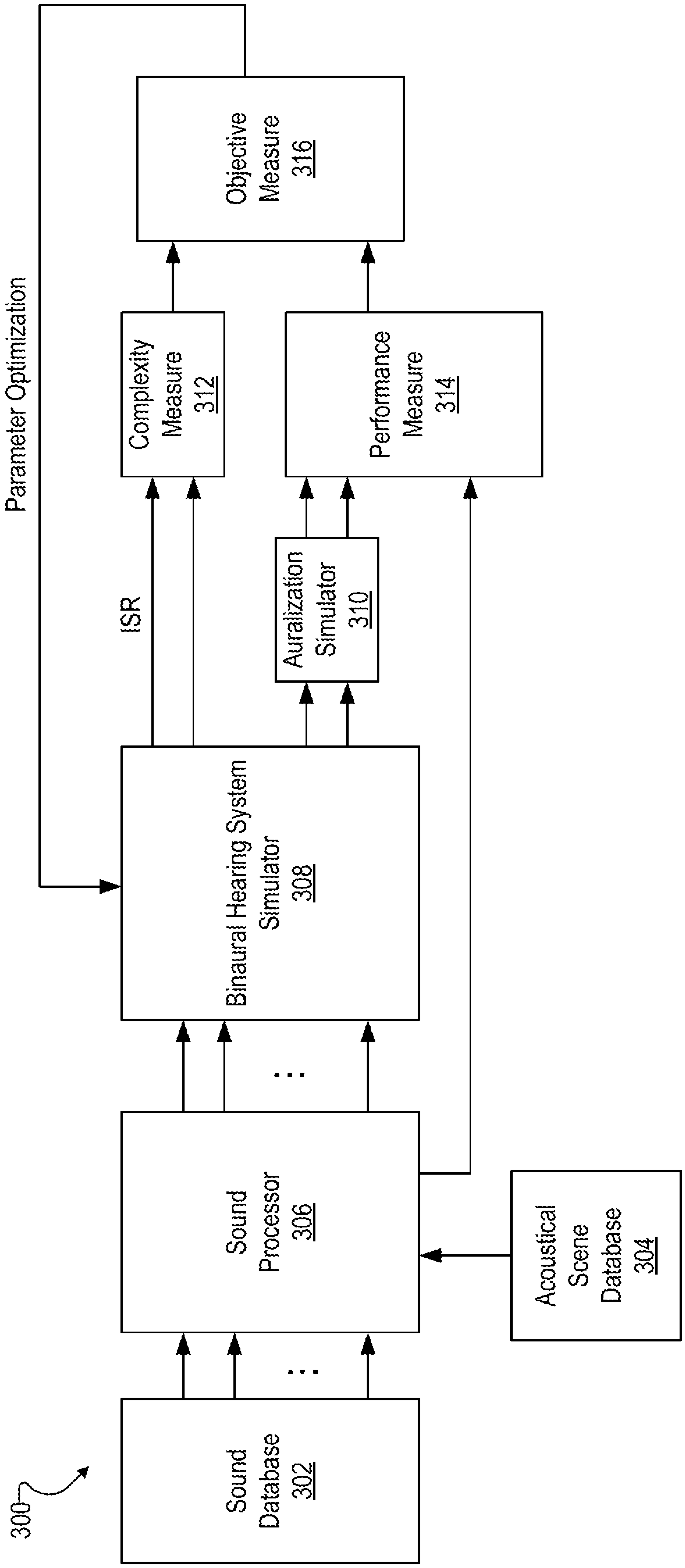

200
Hearing Device
202-1
212-1
212-2
212-N
Preprocessor
204-1
Combinator
208-1
NN
218-1
Postprocessor
210-1
Encoder
206-1
NN
216-1
Encoder
206-2
NN
216-2
214-N
214-2
214-1
NN
218-2
Preprocessor
204-2
Combinator
208-2
Postprocessor
210-2
Hearing Device
202-2

Fig. 2



300
Sound Database 302
Sound Processor 306
Acoustical Scene Database 304
Binaural Hearing System Simulator 308
ISR
Complexity Measure 312
Auralization Simulator 310
Performance Measure 314
Objective Measure 316
Parameter Optimization

Fig. 3

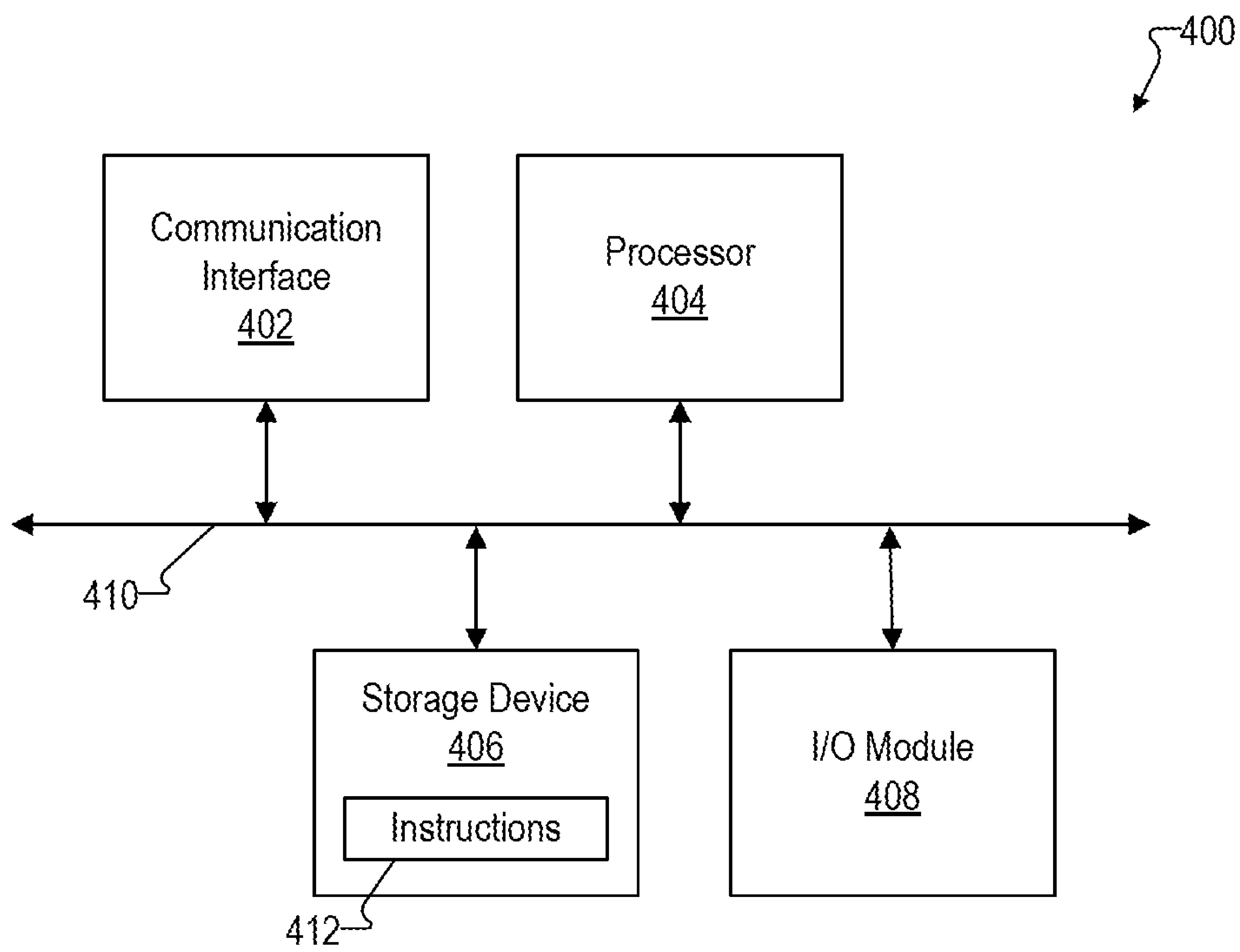

400
Communication Interface 402
Processor 404
410
Storage Device 406
Instructions
412
I/O Module 408

Fig. 4

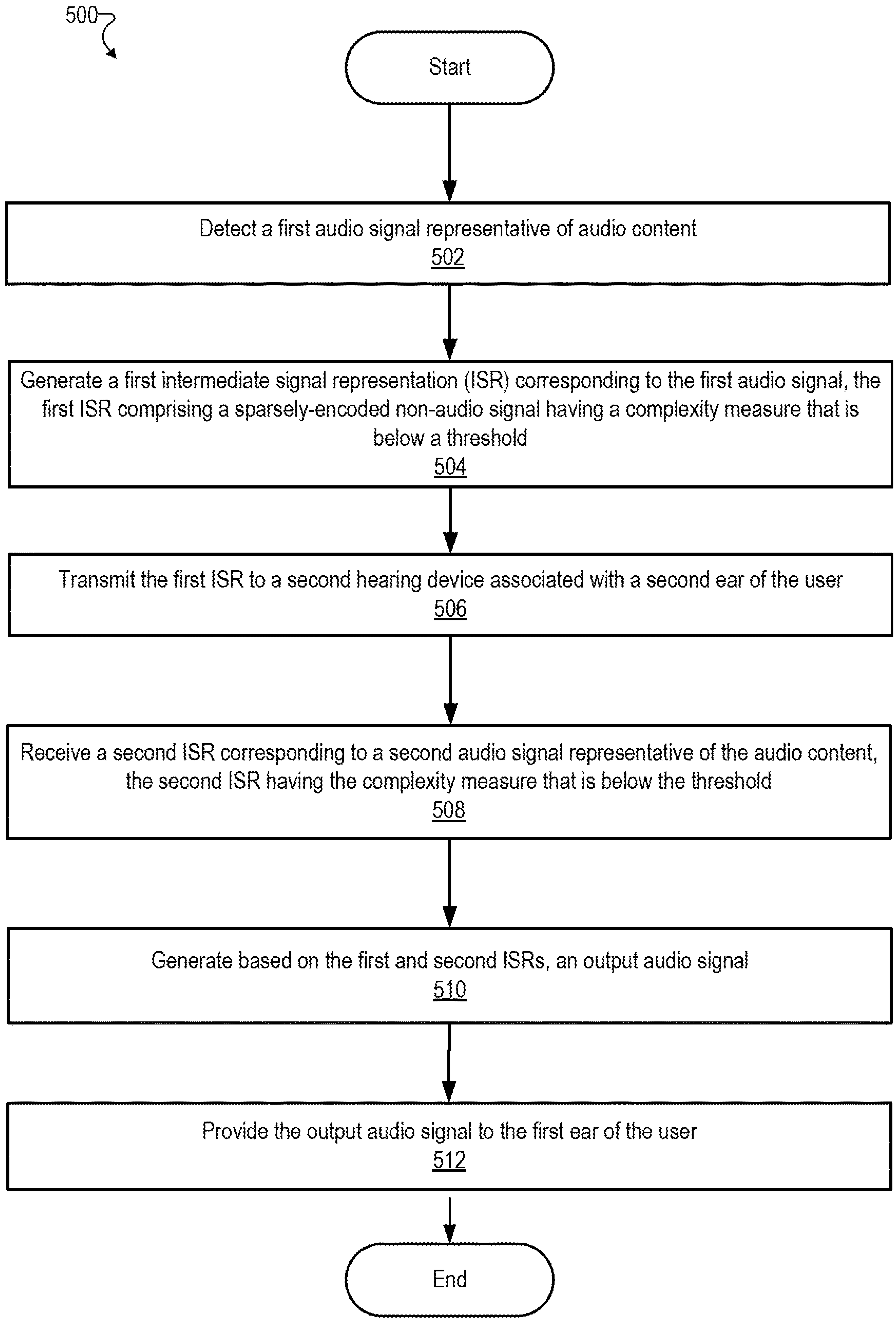

500
Start
Detect a first audio signal representative of audio content
502
Generate a first intermediate signal representation (ISR) corresponding to the first audio signal, the first ISR comprising a sparsely-encoded non-audio signal having a complexity measure that is below a threshold
504
Transmit the first ISR to a second hearing device associated with a second ear of the user
506
Receive a second ISR corresponding to a second audio signal representative of the audio content, the second ISR having the complexity measure that is below the threshold
508
Generate based on the first and second ISRs, an output audio signal
510
Provide the output audio signal to the first ear of the user
512
End

Fig. 5

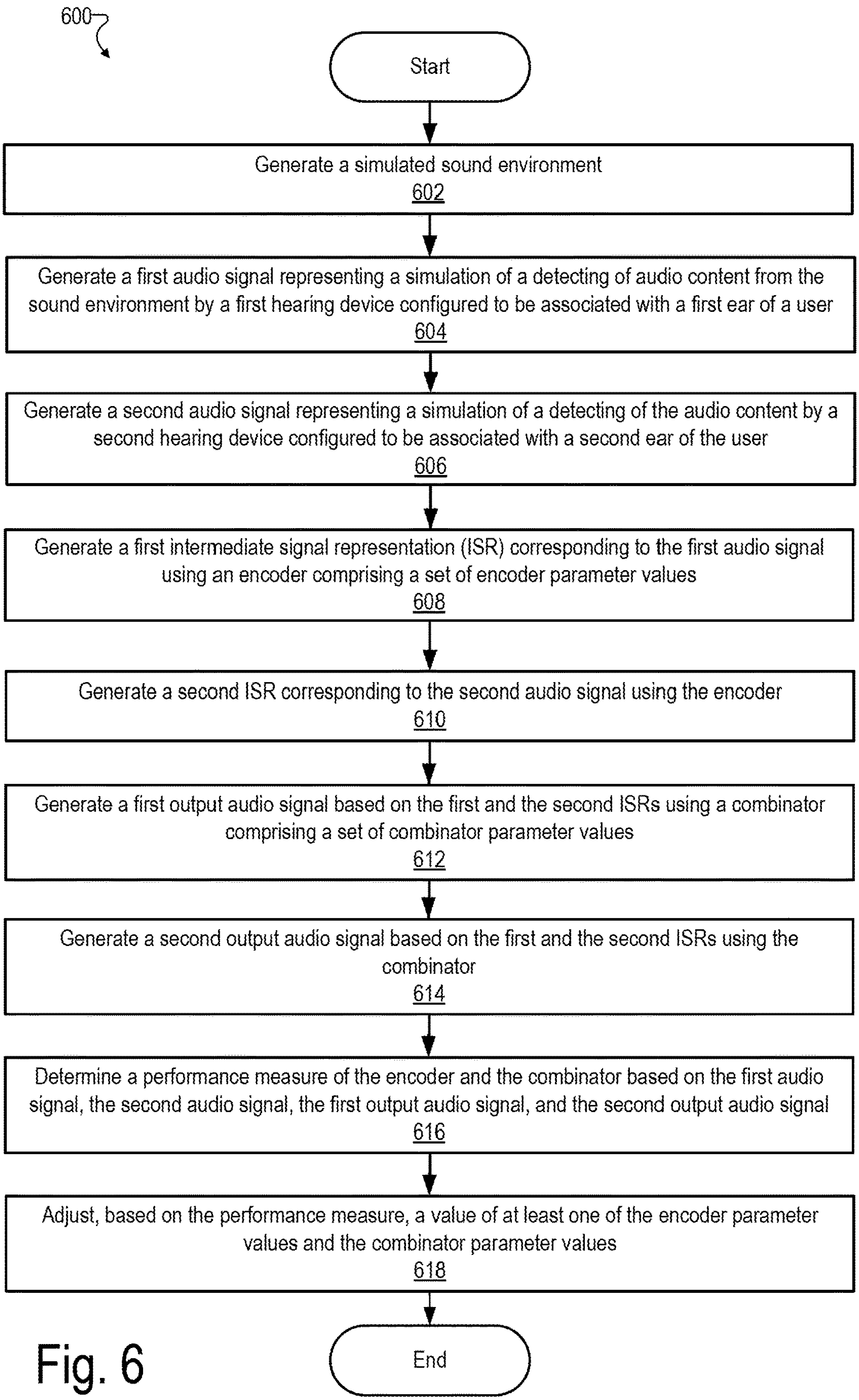

600
Start
Generate a simulated sound environment
602
Generate a first audio signal representing a simulation of a detecting of audio content from the sound environment by a first hearing device configured to be associated with a first ear of a user
604
Generate a second audio signal representing a simulation of a detecting of the audio content by a second hearing device configured to be associated with a second ear of the user
606
Generate a first intermediate signal representation (ISR) corresponding to the first audio signal using an encoder comprising a set of encoder parameter values
608
Generate a second ISR corresponding to the second audio signal using the encoder
610
Generate a first output audio signal based on the first and the second ISRs using a combinator comprising a set of combinator parameter values
612
Generate a second output audio signal based on the first and the second ISRs using the combinator
614
Determine a performance measure of the encoder and the combinator based on the first audio signal, the second audio signal, the first output audio signal, and the second output audio signal
616
Adjust, based on the performance measure, a value of at least one of the encoder parameter values and the combinator parameter values
618
End

Fig. 6

SYSTEMS AND METHODS FOR DATA EXCHANGE BETWEEN BINAURAL HEARING DEVICES

BACKGROUND INFORMATION

A binaural hearing system may include a first hearing device worn behind a first ear of a user and a second hearing device worn behind a second ear of the user. In this configuration, the binaural hearing devices may simultaneously convey sound to both ears of the user. For example, the hearing devices may be implemented by hearing aids configured to provide an amplified version of audio content to the user to enhance hearing by the user.

Hearing devices conventionally have inbuilt microphones configured to detect audio signals presented to the user. Binaural hearing devices may provide various benefits using frontend digital signal processing algorithms involving beamforming, noise reduction, and dynamic range adjustment. However, to maximize the performance of such algorithms, the hearing devices may need to process audio signals as detected by both hearing devices. Thus, the hearing devices may need to transmit audio information to each other. Unfortunately, such transmission may be bandwidth limited and consume a relatively high amount of power.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings illustrate various embodiments and are a part of the specification. The illustrated embodiments are merely examples and do not limit the scope of the disclosure. Throughout the drawings, identical or similar reference numbers designate identical or similar elements.

FIG. **1** illustrates an exemplary hearing system according to principles described herein.

FIG. **2** illustrates an exemplary configuration for data exchange according to principles described herein.

FIG. **3** illustrates an exemplary configuration for parameter optimization according to principles described herein.

FIG. **4** illustrates an exemplary computing device according to principles described herein.

FIGS. **5-6** illustrate exemplary methods according to principles described herein.

DETAILED DESCRIPTION

Exemplary systems and methods for data exchange between binaural hearing devices are described herein. For example, a system may comprise a first hearing device associated with a first ear of a user and a second hearing device associated with a second ear of the user. The first hearing device may be configured to detect a first audio signal representative of audio content, and generate a first intermediate signal representation (ISR) corresponding to the first audio signal, the first ISR comprising a sparsely-encoded non-audio signal having a complexity measure that is below a threshold. The first hearing device may be further configured to transmit the first ISR to the second hearing device. The second hearing device may be configured to detect a second audio signal representative of the audio content, and generate a second ISR corresponding to the second audio signal, the second ISR having the complexity measure that is below the threshold. The second hearing device may be further configured to transmit the second ISR to the first hearing device. The first hearing device may be further configured to generate, based on the first and second ISRs, an output audio signal, and provide the output audio signal to the first ear of the user. Likewise, the second hearing device may be further configured to generate, based on the first and second ISRs, an output audio signal, and provide the output audio signal to the second ear of the user.

The systems and methods described herein may advantageously provide many benefits to users of binaural hearing devices. For example, the hearing devices described herein may provide audio signals that more accurately replicate audio content as perceived by normal hearing than conventional hearing systems. Moreover, the systems and methods described herein provide ISRs that encode the audio information as non-audio signals so that the relevant information may be transmitted between the hearing devices using less bandwidth and operating power than transmitting audio signals or data with an audio signal bitrate. For at least these reasons, the binaural systems and methods described herein may advantageously provide additional functionality and/or features for hearing device users compared to conventional binaural hearing systems. These and other benefits of the systems and methods described herein will be made apparent herein.

FIG. **1** illustrates an exemplary configuration **100** of a binaural hearing system **102** (or simply hearing system **102**). As shown, hearing system **102** includes a first hearing device **104-1** and a second hearing device **104-2** (collectively "hearing devices **104**"). Hearing devices **104** may communicate one with another by way of a wireless communication link **106**.

Hearing devices **104** may each be implemented by any type of hearing device configured to provide or enhance hearing to a user of hearing system **102**. For example, hearing devices **104** may each be implemented by a hearing aid configured to apply amplified audio content to a user, a sound processor included in a cochlear implant system configured to apply electrical stimulation representative of audio content to a user, a sound processor included in an electro-acoustic stimulation system configured to apply electro-acoustic stimulation to a user, a head-worn headset, an ear-worn ear-bud or any other suitable hearing device. In some examples, hearing device **104-1** is of a different type than hearing device **104-2**. For example, hearing device **104-1** may be a hearing aid and hearing device **104-2** may be a sound processor included in a cochlear implant system. As another example, hearing device **104-1** may be a unilateral hearing aid and hearing device **104-2** may be a contralateral routing of signals (CROS) hearing aid.

As shown, each hearing device **104** includes a processor and a memory. For example, hearing device **104-1** includes a processor **108-1** and a memory **110-1**. Likewise, hearing device **104-2** includes a processor **108-2** and a memory **110-2**.

Processors **108** (e.g., processor **108-1** and processor **108-2**) are configured to perform various processing operations, such as processing audio content received by hearing devices **104** and transmitting data to each other. Processors **108** may each be implemented by any suitable combination of hardware and software.

Memories **110** (e.g., memory **110-1** and memory **110-2**) may be implemented by any suitable type of non-transitory computer readable storage medium and may maintain (e.g., store) data utilized by processors **108**. For example, memories **110** may store data representative of an operation program that specifies how each processor **108** processes and delivers audio content to a user. To illustrate, if hearing device **104-1** is a hearing aid, memory **110-1** may maintain data representative of an operation program that specifies an audio amplification scheme (e.g., amplification levels, etc.) used by processor **108-1** to deliver acoustic content to the user. As another example, if hearing device **104-1** is a sound processor included in a cochlear implant system, memory **110-1** may maintain data representative of an operation program that specifies a stimulation scheme used by hearing device **104-1** to direct a cochlear implant to apply electrical stimulation representative of acoustic content to the user.

Hearing devices **104** may communicate with each other (e.g., by transmitting data) by way of a wireless communication link **106** that interconnects hearing devices **104**. Wireless communication link **106** may include any suitable wireless communication link as may serve a particular implementation.

FIG. **2** illustrates an exemplary configuration **200** of a binaural hearing system (e.g., hearing system **102**). Configuration **200** includes hearing devices **202** (e.g., hearing device **202-1** and hearing device **202-2**), which may each be configured to be associated with an ear of a user. As used herein, a hearing device "associated with" an ear of a user is configured to be used to provide an output audio signal to the ear. For example, hearing device **202-1** may be worn on or within a right ear of the user and configured to provide an output audio signal to the right ear. Likewise, hearing device **202-2** may be worn on or within a left ear of the user and configured to provide an output audio signal to the left ear.

As shown, hearing device **202-1** includes a preprocessor **204-1**, an encoder **206-1**, a combinator **208-1**, and a postprocessor **210-1**. Similarly, hearing device **202-2** includes a preprocessor **204-2**, an encoder **206-2**, a combinator **208-2**, and a postprocessor **210-2**. Preprocessors **204**, encoders **206**, combinators **208**, and postprocessors **210** may each be implemented as a software/firmware module, a hardware circuit, and/or any suitable combination of hardware and software/firmware. For example, preprocessors **204**, encoders **206**, combinators **208**, and postprocessors **210** may be implemented in one or more processors (e.g., processor **108**) of hearing devices **202**.

Hearing device **202-1** further includes an array of microphones **212** (e.g., microphones **212-1** through **212**-N). Likewise, hearing device **202-2** also includes an array of microphones **214** (e.g., microphones **214-1** through **214**-N). Each of microphones **212** and microphones **214** may be implemented by any suitable audio detection device and is configured to detect an audio signal provided to a user of hearing devices **202**. The audio signal may include, for example, audio content (e.g., music, speech, noise, etc.) generated by one or more audio sources included in an environment of the user, including the user. Microphones **212** and microphones **214** may be included in or communicatively coupled to hearing device **202-1** and hearing device **202-2**, respectively, in any suitable manner.

Microphones **212** may be configured to detect audio content from different locations, such as different positions on hearing device **202-1**. Microphones **214** may be likewise configured to detect audio content from different locations, such as different positions on hearing device **202-2**. Further, microphones **214** may detect the audio content from locations different from microphones **212** as well as each other. For instance, as hearing device **202-1** and hearing device **202-2** are configured for different ears of the user, audio signals detected by microphones **212** and microphones **214** of a same audio content may vary based on the environment of the user, including directions of sources of the audio content, absorption and reflection off of objects and people (including the user) in the environment, etc.

The audio signals detected by microphones **212** may be received by preprocessor **204-1**, which may perform various preprocessing functions on the audio signals. For example, preprocessor **204-1** may perform analog-to-digital (A/D) conversion, filtering, compression, and/or any other suitable preprocessing algorithms on the audio signals. Preprocessor **204-1** may perform the preprocessing on each of the audio signals individually and output the preprocessed audio signals, outputting a same number of signals as received from microphones **212**. Preprocessor **204-1** may output the preprocessed audio signals to both encoder **206-1** and combinator **208-1**. Similarly, preprocessor **204-2** may receive audio signals detected by microphones **214** and perform various preprocessing functions on the audio signals received. Preprocessor **204-2** may likewise output the preprocessed audio signals to encoder **206-2** and combinator **208-2**.

Encoder **206-1** may receive the preprocessed audio signals from preprocessor **204-1** and generate an intermediate signal representation (ISR) corresponding to the preprocessed audio signals. The ISR may be configured to encode the information from the preprocessed audio signals most relevant to reconstructing the preprocessed audio signals for further processing, such as for beamforming, noise reduction, etc. However, the ISR may also be configured with a threshold complexity so that the ISR may be transmitted efficiently, such as via a low-latency wireless connection or any such suitable connection (e.g., wireless communication link **106**). Thus, the ISR may be implemented as any suitable latent representation of the audio signals, such as a signal that encodes the audio signals received by encoder **206-1** with a lower dimensionality than the audio signals. For instance, the ISR may be a sparsely-encoded (e.g., an encoding of data comprising mostly zeros relative to non-zeros) non-audio signal that corresponds to a combination of the preprocessed audio signals.

In some examples, encoder **206-1** may be implemented, at least in part, using a machine learning algorithm such as a neural network **216-1**. Neural network **216-1** may include any suitable neural network, such as an artificial neural network (ANN), a convolutional neural network (CNN), a recurrent neural network (RNN), etc. In some examples, neural network **216-1** may be implemented in encoder **206-1** using a dedicated ANN accelerator. Neural network **216-1** may be trained to receive the preprocessed audio signals and generate the ISR based on the received audio signals. The training of neural network **216-1** may configure the ISR to optimize parameters for reconstruction of the audio signal while minimizing complexity of the ISR. The training of neural network **216-1** is described further herein.

In some examples, encoder **206-1** may further compress and/or sub-sample the generated ISR (which may itself also be considered an ISR). Encoder **206-1** outputs the ISR to hearing device **202-2** (e.g., combinator **208-2**). Similarly, encoder **206-2** may encode preprocessed audio signals received from preprocessor **204-2** and output an ISR corresponding to the audio signals received by hearing device **202-2** to hearing device **202-1** (e.g., combinator **208-1**).

Combinator **208-1** may receive the ISR corresponding to the audio signals received by hearing device **202-2**, as well as the preprocessed audio signals from preprocessor **204-1**. Further, in some examples, combinator **208-1** may receive the ISR generated by encoder **206-1** that is transmitted to hearing device **202-2**. Combinator **208-1** may generate an output audio signal based on these received input signals. In some examples, combinator **208-1** may include a machine learning algorithm such as a neural network **218-1** that is configured to generate the output audio signal based on the input signals. Neural network **218-1** may include any suitable neural network and may be trained to work with neural network **216-1** to optimize the configuration of the ISRs and the output audio signal reconstructed from the ISRs. In some examples, neural network **218-1** may be implemented in combinator **208-1** using a dedicated ANN accelerator. The training of neural network **218-1** is described further herein.

Generating the output audio signal by combinator **208-1** may include additional processing of the ISRs. For example, combinator **208-1** may process the ISRs to replicate the audio content as experienced by normal hearing, which may include algorithms to compensate for the positioning of microphones **214** that result in differences in the detected audio signals from audio signals detected by a normal-hearing ear (e.g., filtering by a pinna of the ear, reduced ability to localize sound sources, reduced speech intelligibility, reduced parsing of complex auditory scenes, etc.). Such processing may include algorithms such as beamforming, noise reduction, dynamic range adjustment, sound quality enhancement, dereverberation, adaptive spatial directivity adjustment, etc. The information from the audio signals that is used for such algorithms may vary depending on the algorithm. Thus the ISRs may be configured based on the processing that is to be performed by combinator **208-1**, which may vary based on a sound environment of the user, a sound processing program of hearing device **202-1**, etc. Further, parameters of combinator **208-1** (e.g., neural network **218-1**) may be optimized for the processing performed by combinator **208-1**.

The audio signal output by combinator **208-1** may be received by postprocessor **210-1**. Postprocessor **210-1** may perform various postprocessing functions on the output audio signal. For example, postprocessor **210-1** may perform filtering, compression, digital-to-analog (D/A) conversion, and/or any other suitable postprocessing on the audio signals. Postprocessor **210-1** may provide the postprocessed audio signal to the ear of the user. In some examples, postprocessor **210-1** and/or its functionality may be omitted and the output audio signal provided by combinator **208-1** may be provided to the user.

Similarly, combinator **208-2** may generate an output audio signal to be provided to a corresponding ear of the user based on input signals received from encoder **206-1**, encoder **206-2**, and preprocessor **204-2**. Postprocessor **210-2** may also perform various postprocessing functions on the output audio signal. The output audio signals provided to the user by hearing devices **202** may thus be processed to provide audio signals representing audio content as would be experienced with normal hearing, including binaural cues.

FIG. **3** illustrates exemplary configuration **300** for parameter optimization for data exchange between binaural hearing devices. Configuration **300** may be implemented on any suitable processor, including a processor on a hearing device (e.g., hearing devices **202**), one or more processors in a computer, a supercomputer, a network of computers, etc. Configuration **300** includes a sound database **302**, an acoustical scene database **304**, a sound processor **306**, a binaural hearing system simulator **308**, an auralization simulator **310**, a complexity measure module **312**, a performance measure module **314**, and an objective measure module **316**. Components of configuration **300** may each be combined into fewer components, further subdivided into more components, and/or implemented on one or more processors and/or devices.

As shown, sound processor **306** may receive inputs from a sound database **302** and an acoustical scene database **304**. For instance, sound database **302** may include data representative of characteristic sounds (e.g., speech, music, noise, ambient background noise, etc.) that may be encountered in a wide variety of sound environments. Acoustical scene database **304** may include data representative of various types of environments in which the sounds from sound database **302** may be inserted and altered based on the environment (e.g., a moving car, a concert hall, over a phone, etc.).

Sound processor **306** may receive sets of inputs from sound database **302** and acoustical scene database **304** that simulate audio content that may be encountered in one or more specific sound environments. Sound processor **306** may process the inputs to generate a simulated sound environment and simulated microphone input of the audio content as would be detected by microphones of a hearing system (e.g., microphones **212** and **214** of configuration **200**) in the simulated sound environment. Sound processor **306** may process the inputs to generate such a simulation using any suitable algorithms, such as amplification, sound staging, reverberation, microphone head-related transfer functions (HRTF), etc.

Sound processor **306** may provide the simulated microphone input to binaural hearing system simulator **308**. Binaural hearing system simulator may simulate functionality of a hearing system such as hearing devices **202**. Thus, binaural hearing system simulator **308** may generate ISRs associated with the simulated microphone inputs received from sound processor **306** and output audio signals that would be provided to a user of the hearing system. Binaural hearing system simulator **308** may output the generated ISRs to complexity measure module **312** and the output audio signals to auralization simulator **310**.

Auralization simulator **310** may receive the output audio signals generated by binaural hearing system simulator **308** and simulate how such audio signals would be perceived by the user. Thus, in some examples, auralization simulator **310** may include an individualized hearing model of the user that models a specific user's hearing loss. In other examples, auralization simulator **310** may base the simulation on a generic or generalized hearing model. Auralization simulator **310** provides a simulated audio output to performance measure module **314**.

Performance measure module **314** receives the simulated audio output from auralization simulator **310** as well as an input reference from sound processor **306**. The input reference may be any suitable audio signal that is used to compare to the output audio signal generated by binaural hearing system simulator **308** based on a reconstructing and processing of ISRs. For example, the input reference may be the original simulated audio content generated by sound processor **306**. Additionally or alternatively, the input reference may be the simulated microphone input of the audio content. Additionally or alternatively, the input reference may be the audio content processed by an auralization simulation. Additionally or alternatively, the input reference may be an idealized output of hearing devices **202**.

Performance measure module **314** may compare the inputs received from auralization simulator **310** to the input reference to determine a performance measure of binaural hearing system simulator **308**. Specifically, the performance measure may gauge an effectiveness of a set of parameters for an encoding of the ISRs (e.g., encoders **206**) and a reconstructing of audio signals from the ISRs (e.g., combinators **208**) to generate output audio signals that replicate the audio content as experienced by normal hearing. For example, the performance measure may include metrics such as speech intelligibility index, perceptual evaluation of speech quality (PESQ), speech transmission index (STI), mean opinion score, etc., while the parameters may include weights for neural networks for encoders **206** and combinators **208**. In some examples, the performance measure module **314** may also be implemented using a machine learning algorithm, such as a neural network.

Complexity measure module **312** receives the ISRs generated by binaural hearing system simulator **308**. Complexity measure module **312** may determine any suitable complexity measure of the ISRs. The complexity measure may be any objective measure of resources required to transmit the ISRs, such as an average bitrate of the ISRs.

Objective measure module **316** may receive the complexity measure output by complexity measure module **312** and the performance measure output by performance measure module **314**. Objective measure module **316** may determine an overall objective measure of the binaural hearing system simulator **308** based on the performance measure and the complexity measure. For example, the overall objective measure may be any suitable combination of the performance measure and the complexity measure to maximize the performance of the audio signal output by binaural hearing system simulator **308** while generating ISRs having a complexity measure that is below a predetermined threshold complexity measure. The predetermined threshold complexity measure may be representative of any suitable complexity level, which may be based on a capacity of a communication link between hearing devices of the binaural hearing system. For example, a threshold complexity measure may be representative of an average bitrate of the ISRs, such as anywhere between 1 and 100 kilobits per second (kbps) or any other suitable bitrate. The threshold complexity measure may additionally or alternatively be any other suitable metric as may serve a particular implementation.

Objective measure module **316** provides the overall objective measure to binaural hearing system simulator **308** so that the machine learning algorithms (e.g., neural networks **216** and **218**) may be trained based on the feedback. For example, binaural hearing system simulator **308** may adjust, based on the overall objective measure, one or more parameters of encoder **306** (e.g., neural networks **216**) and/or combinators **208** (e.g., neural networks **218**) to determine optimal configurations of the ISRs and for generating and reconstructing the ISRs. Additionally or alternatively, such adjustments may be made based on the performance measure and/or the complexity measure. In some examples, the adjusting of parameters may be performed successively and/or iteratively, such as an adjusting of parameters of encoders **306** while keeping parameters of combinators **308** the same and then vice versa.

As the hearing system (e.g., neural networks **216** and **218**) is trained using audio content from simulated sound environments, any suitable number of sound environments may be generated to provide input for the training. Furthermore, as described, the optimization of the ISRs may include configuring different ISRs for different circumstances, which may include sound environments, acoustical scenes, sound processing programs, individualized hearing loss models, etc. In some examples, the ISRs may be further optimized for individualization in a fitting session for a user or by the user via a mobile app.

In some examples, configuration **300** may be implemented on the hearing system (e.g., hearing devices **202**), in which case audio content may be detected from actual sound environments rather than simulated sound environments and binaural hearing system simulator **308** may instead be the actual hearing system. In such cases, the hearing system may continue to optimize while in use (or during specific training periods). The hearing system may receive additional input from the user (e.g., indications of improved or worsening performance) for such optimization.

FIG. **4** illustrates an exemplary computing device **400** that may be specifically configured to perform one or more of the processes described herein. Any of the systems, units, computing devices, and/or other components described herein may be implemented by computing device **400**.

As shown in FIG. **4**, computing device **400** may include a communication interface **402**, a processor **404**, a storage device **406**, and an input/output ("I/O") module **408** communicatively connected one to another via a communication infrastructure **410**. While an exemplary computing device **400** is shown in FIG. **4**, the components illustrated in FIG. **4** are not intended to be limiting. Additional or alternative components may be used in other embodiments. Components of computing device **400** shown in FIG. **4** will now be described in additional detail.

Communication interface **402** may be configured to communicate with one or more computing devices. Examples of communication interface **402** include, without limitation, a wired network interface (such as a network interface card), a wireless network interface (such as a wireless network interface card), a modem, an audio/video connection, and any other suitable interface.

Processor **404** generally represents any type or form of processing unit capable of processing data and/or interpreting, executing, and/or directing execution of one or more of the instructions, processes, and/or operations described herein. Processor **404** may perform operations by executing computer-executable instructions **412** (e.g., an application, software, code, and/or other executable data instance) stored in storage device **406**.

Storage device **406** may include one or more non-transitory computer readable data storage media, devices, or configurations and may employ any type, form, and combination of data storage media and/or device. For example, storage device **406** may include, but is not limited to, any combination of the non-volatile media and/or volatile media described herein. Electronic data, including data described herein, may be temporarily and/or permanently stored in storage device **406**. For example, data representative of computer-executable instructions **412** configured to direct processor **404** to perform any of the operations described herein may be stored within storage device **406**. In some examples, data may be arranged in one or more databases residing within storage device **406**.

I/O module **408** may include one or more I/O modules configured to receive user input and provide user output. I/O module **408** may include any hardware, firmware, software, or combination thereof supportive of input and output capabilities. For example, I/O module **408** may include hardware and/or software for capturing user input, including, but not limited to, a keyboard or keypad, a touchscreen component (e.g., touchscreen display), a receiver (e.g., an RF or infrared receiver), motion sensors, and/or one or more input buttons.

I/O module **408** may include one or more devices for presenting output to a user, including, but not limited to, a graphics engine, a display (e.g., a display screen), one or more output drivers (e.g., display drivers), one or more audio speakers, and one or more audio drivers. In certain embodiments, I/O module **408** is configured to provide graphical data to a display for presentation to a user. The graphical data may be representative of one or more graphical user interfaces and/or any other graphical content as may serve a particular implementation.

FIG. **5** illustrates an exemplary method **500**. One or more of the operations shown in FIG. **5** may be performed by any of the hearing devices described herein. While FIG. **5** illustrates exemplary operations according to one embodiment, other embodiments may omit, add to, reorder, and/or modify any of the operations shown in FIG. **5**. Each of the operations shown in FIG. **5** may be performed in any of the ways described herein.

At operation **502**, a hearing device configured to be associated with a first ear of a user detects a first audio signal representative of audio content.

At operation **504**, the hearing device generates a first ISR corresponding to the first audio signal, the first ISR comprising a sparsely-encoded non-audio signal having a complexity measure that is below a threshold.

At operation **506**, the hearing device transmits the first ISR to a second hearing device associated with a second ear of the user.

At operation **508**, the hearing device receives a second ISR corresponding to a second audio signal representative of the audio content, the second ISR having the complexity measure that is below the threshold.

At operation **510**, the hearing device generates based on the first and second ISRs, an output audio signal.

At operation **512**, the hearing device provides the output audio signal to the first ear of the user.

FIG. **6** illustrates an exemplary method **600**. One or more of the operations shown in FIG. **6** may be performed by any of the processors described herein. While FIG. **6** illustrates exemplary operations according to one embodiment, other embodiments may omit, add to, reorder, and/or modify any of the operations shown in FIG. **6**. Each of the operations shown in FIG. **6** may be performed in any of the ways described herein.

At operation **602**, a processor generates a simulated sound environment.

At operation **604**, the processor generates a first audio signal representing a simulation of a detecting of audio content from the sound environment by a first hearing device configured to be associated with a first ear of a user.

At operation **606**, the processor generates a second audio signal representing a simulation of a detecting of the audio content by a second hearing device configured to be associated with a second ear of the user.

At operation **608**, the processor generates a first intermediate signal representation (ISR) corresponding to the first audio signal using an encoder comprising a set of encoder parameter values.

At operation **610**, the processor generates a second ISR corresponding to the second audio signal using the encoder.

At operation **612**, the processor generates a first output audio signal based on the first and the second ISRs using a combinator comprising a set of combinator parameter values.

At operation **614**, the processor generates a second output audio signal based on the first and the second ISRs using the combinator.

At operation **616**, the processor determines a performance measure of the encoder and the combinator based on the first audio signal, the second audio signal, the first output audio signal, and the second output audio signal.

At operation **618**, the processor adjusts, based on the performance measure, a value of at least one of the encoder parameter values and the combinator parameter values.

In the preceding description, various exemplary embodiments have been described with reference to the accompanying drawings. It will, however, be evident that various modifications and changes may be made thereto, and additional embodiments may be implemented, without departing from the scope of the invention as set forth in the claims that follow. For example, certain features of one embodiment described herein may be combined with or substituted for features of another embodiment described herein. The description and drawings are accordingly to be regarded in an illustrative rather than a restrictive sense.

What is claimed is:

1. A system comprising:
a first hearing device associated with a first ear of a user and a second hearing device associated with a second ear of the user;
the first hearing device configured to:
detect a first audio signal representative of audio content,
generate a first intermediate signal representation (ISR) based on the first audio signal, the first ISR comprising a signal encoding the first audio signal and having a complexity measure that is below a threshold, and
transmit the first ISR to the second hearing device;
the second hearing device configured to:
detect a second audio signal representative of the audio content,
generate a second ISR based on the second audio signal, the second ISR comprising a signal encoding the second audio signal and having the complexity measure that is below the threshold, and
transmit the second ISR to the first hearing device;
the first hearing device further configured to:
generate, based on the first and second ISRs, an output audio signal, and
provide the output audio signal to the first ear of the user.

2. The system of claim **1**, wherein the second hearing device further configured to:
generate, based on the first and second ISRs, an additional output audio signal; and
provide the additional output audio signal to the second ear of the user.

3. The system of claim **1**, wherein the generating the first ISR comprises using a first machine learning algorithm and the generating the second ISR comprises using a second machine learning algorithm.

4. The system of claim **3**, wherein the first machine learning algorithm and the second machine learning algorithm include a same algorithm.

5. The system of claim **3**, wherein the generating the output audio signal comprises using a third machine learning algorithm.

6. The system of claim **5**, wherein:
the first machine learning algorithm comprises a first neural network;
the second machine learning algorithm comprises a second neural network;
the third machine learning algorithm comprises a third neural network; and
the first hearing device is further configured to select parameters for at least one of the first neural network and the third neural network based on at least one of an environment of the user and a hearing loss model of the user.

7. The system of claim 6, wherein:

the first hearing device is further configured to select a processing algorithm for generating the output audio signal; and

the selecting the parameters for the at least one of the first neural network and the third neural network is further based on the selecting the processing algorithm for the generating the output audio signal.

8. The system of claim 1, wherein:

the first hearing device is further configured to detect a third audio signal representative of the audio content;

the generating the first ISR comprises generating the first ISR to correspond to a combination of the first and third audio signals;

the second hearing device is further configured to detect a fourth audio signal representative of the audio content; and

the generating the second ISR comprises generating the second ISR to correspond to a combination of the second and fourth audio signals.

9. The system of claim 8, wherein the generating the output audio signal comprises processing the first and second ISRs using a beamforming algorithm.

10. The system of claim 8, wherein the generating the output audio signal comprises processing the first and second ISRs for adaptive spatial directivity adjustment.

11. The system of claim 1, wherein:

the first hearing device comprises a first artificial neural network (ANN) accelerator configured to generate the first ISR; and

the second hearing device comprises a second ANN accelerator configured to generate the second ISR.

12. A method comprising:

detecting, by a first hearing device associated with a first ear of a user, a first audio signal representative of audio content;

generating, by the first hearing device, a first intermediate signal representation (ISR) based on the first audio signal, the first ISR comprising a signal encoding the first audio signal and having a complexity measure that is below a threshold;

transmitting, by the first hearing device, the first ISR to a second hearing device associated with a second ear of the user;

receiving, by the first hearing device, a second ISR based on a second audio signal representative of the audio content, the second ISR comprising a signal encoding the second audio signal and having the complexity measure that is below the threshold;

generating, by the first hearing device, based on the first and second ISRs, an output audio signal; and

providing, by the first hearing device, the output audio signal to the first ear of the user.

13. The method of claim 12, wherein:

the generating the first ISR comprises using a first machine learning algorithm; and

the generating the output audio signal comprises using a second machine learning algorithm.

14. The method of claim 13, wherein:

the first machine learning algorithm comprises a first neural network;

the second machine learning algorithm comprises a second neural network; and

the method further comprises selecting, by the first hearing device, parameters for at least one of the first neural network and the second neural network based on at least one of an environment of the user and a hearing loss model of the user.

15. The method of claim 14, further comprising selecting, by the first hearing device, a processing algorithm for generating the output audio signal;

wherein the selecting the parameters for the at least one of the first neural network and the second neural network is further based on the selecting the processing algorithm for the generating the output audio signal.

16. The method of claim 12, further comprising detecting, by the first hearing device, a third audio signal representative of the audio content, and wherein:

the generating the first ISR comprises generating the first ISR to correspond to a combination of the first and third audio signals.

17. The method of claim 16, wherein the generating the output audio signal comprises processing the first and second ISRs using at least one of a beamforming algorithm and an adaptive spatial directivity adjustment algorithm.

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